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13. ABSTRACT *(Maximum 200 words)*

Results are presented from an experimental study of droplet phenomena in diesel engine and gas turbine combustor simulated flows. Three specific phenomena have been studied: i) the use of exciplex fluorescence to characterize the vaporization of liquid droplets in unsteady flows, ii) the enhanced secondary breakup of liquid droplets in flows with intense turbulence, and iii) the behavior of liquid jets injected into supercritical environments.

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The Effect of Turbulence on Droplet Drag, Dispersion, Vaporization and Secondary Breakup in Diesel Fuel Sprays

Final Technical Report

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I. Summary of Research

Results are presented from an experimental study of droplet phenomena in diesel engine and gas turbine combustor simulated flows. Three specific phenomena have been studied: i) the use of exciplex fluorescence to characterize the vaporization of liquid droplets in unsteady flows, ii) the enhanced secondary breakup of liquid droplets in flows with intense turbulence, and iii) the behavior of liquid jets injected into supercritical environments.

A. The Development and Use of an Exciplex Vapor/Liquid Visualization Technique to Study the Effect of an Acoustic Field on a Vaporizing Droplet

A study of droplet vaporization in a longitudinal acoustic field has been performed to determine how the acoustic field alters the vaporization process at time scales defined by the period of the imposed acoustic field. Traditional methods used to study droplet vaporization, i.e., the measurement of the change in droplet diameter with time, cannot be accurately employed at such short time scales. Instead, an exciplex vapor/liquid visualization technique has been refined and implemented to allow the liquid and vapor phase fluorescence signals from a liquid droplet and its associated fuel vapor wake to be spectrally separated and imaged independently.

The exciplex vapor/liquid visualization technique employed in this study is based on the exciplex formed between N,N,N',N'-tetramethyl-1,4-phenylenediamine (TMPD) and 1-methylnaphthalene (1MN), and has been optimized by obtaining spectral data on each of the components which contribute to the overall fluorescence. Measurements of the fluorescence spectra and quantum yields are presented, and these data are used to select the most appropriate spectral bandpass filters to maximize the spectral separation between the liquid and vapor phases, based on the system constraints.

Droplets suspended in a high temperature crossflow have been imaged using this technique. Images obtained at different Reynolds numbers showed the degree of separation that can be obtained and verified the technique was working as desired. These images were also able to show the distinct differences in the fuel vapor wakes at the various flow conditions.

To study the interaction between droplet vaporization and a longitudinal acoustic field, an optically accessible test chamber has been built. The unique feature of this test chamber is its ability to generate a longitudinal acoustic disturbance in the flow, with frequencies ranging from 70-470 Hz, with acoustic-to-ambient pressure ratios of 0.1 or higher. The test chamber also includes access for measuring equipment, i.e., thermocouples and pressure transducers, and a droplet suspension device.

To simulate a vaporizing droplet, a suspended porous sphere was used. For the acoustically perturbed droplet vaporization studies, three acoustic frequencies were used, 210 Hz, 287 Hz, and 459 Hz. In addition, a steady case is included to serve as a

reference condition. Sequences of images, taken at discrete phases of the imposed acoustic field, offer visual evidence of the evolution of the spatial distribution of fuel vapor in the droplet wake. In addition, plots of the axial fuel vapor distribution and total amount of fuel vapor in the wake, show variations over the course of the acoustic cycle.

The results show that the spatial distribution and the amount of fuel vapor in the wake can be driven by a longitudinal acoustic field and respond at the imposed frequency. These variations offer evidence that droplet vaporization may be an important mechanism in initiating and sustaining combustion instabilities.

B. Secondary Droplet Breakup in Highly Turbulent Flowfields

An experimental investigation was undertaken to study the secondary breakup of liquid droplets by gaseous inertial forces in turbulent flows. This was accomplished by injecting single droplets of methanol, tetradecane, and n-heptane into well-characterized air flowfields with three discrete levels of turbulence. Laminar flowfields at pressures of 1 and 5 atm were used to assure that the results of the present experiment were in accord with those of previous investigations. Two additional 5 atm flowfields permitted determination of the effects of moderate and high levels of turbulence, with relative intensities of 30% and 45%, respectively.

The experimental results indicated that the breakup of droplets in turbulent flows required a lower ratio of mean aerodynamic-to-surface forces (Weber number), compared to that in laminar flows. This ratio continued to decrease as the relative turbulence intensity increased. In addition, the form of droplet breakup was different. In laminar flows, droplets were observed to stretch into "bags" and burst into several large droplets from the toroidal rim and numerous small droplets from the bag. In the turbulent flowfields, however, the droplets initially broke into several similarly-sized daughters. This has been termed "bulgy" breakup. At higher Weber numbers, breakup was dominated by the bag mechanism. These trends were reflected in the post-breakup fragment distributions.

The results of all three of the fuels utilized in this investigation were similar, except that for the 5 atm flowfields, the critical Weber numbers required to effect droplet breakup were somewhat higher for tetradecane. This trend was not observed for the 1 atm laminar flowfield, leading to the conclusion that somewhat elevated pressures may affect the breakup dynamics for this fuel. Although the critical pressure for tetradecane is relatively low (15.5 atm), reduced surface tensions were eliminated as the cause for this phenomenon.

An order of magnitude analysis was conducted to determine the effects of different time and length scales on breakup in turbulent flowfields. The results indicated that eddies must be at least as large as the initial droplet diameter in order to significantly affect breakup, and that eddies an order of magnitude larger are probably most influential. Specifically, examination of characteristic time scales led to speculation that eddy sizes between ten times the initial droplet diameter and the

largest scales in the flowfield are responsible for bulgy breakup. Additionally, by redefining the aerodynamic forces in terms of alternate velocity scales, the critical Weber number for bag breakup in laminar flows was recovered when using the combination of the bulk flow and fastest moving eddies ten times the size of the initial droplet diameter.

C. An Experimental Study of the Behavior of Liquid Jets Subjected to Thermodynamic Subcritical and Supercritical Conditions

As combustion chamber pressures and temperatures have risen, the possibility of liquid fuel injection into a supercritical ambient environment has been realized. If the pressure and temperature within a combustion chamber exceed the critical pressure and temperature of the injected liquid fuel, the potential for the fuel achieving a supercritical state exists. If the fuel (or more accurately, the fuel/air mixture) reaches critical conditions, surface tension vanishes while the vapor/liquid density ratio approaches unity, possibly altering the mixing behavior of the fuel and air from the well-studied behavior of jets injected into pressures and temperatures much less than the liquid critical point. The absence of surface tension alone would allow enhanced mixing of the components due to the lack of a surface tension force. Even if critical conditions are not reached, significant changes in fuel and ambient thermophysical properties alter jet breakup characteristics from those jets injected into environments of more modest pressures and temperatures.

To elucidate these issues, an experimental study of n-pentane jet breakup in high pressure and high temperature nitrogen environments has been performed. Specifically, n-pentane at 20°C was injected transversely into nitrogen through a plain orifice atomizer at velocities varying from 1.0 m/sec to 6.0 m/sec. The nitrogen crossflow Reynolds number was varied from 2 to 15 (calculated with respect to the jet diameter) while the nitrogen temperature and pressure were varied from 20°C to 300°C and 100 psig to 1500 psig, respectively. The experiments were carried out in an optically accessible test chamber to enable the jets' behavior to be viewed upon backlit illumination with a strobe light. Additionally, two-dimensional spontaneous Raman imaging of the jet was performed to attempt to measure the n-pentane concentration immediately downstream of the jets as a means of quantifying jet vaporization.

An initial investigation of the jets' behavior revealed possible evidence of attainment of the mixture critical point. In particular, the distinct surfaces of some of the liquid structures appeared to fade at the highest test pressures which were well above the critical pressure of n-pentane. With this in mind, an analysis of the jets' breakup mechanism, continuous length, drag coefficient and wake fuel concentration was conducted to determine if jet behavior at extreme pressures and temperatures could be explained by the characteristic decrease in surface tension and increase in gas/liquid density ratio as the critical point is reached. Though not all results could be explained by the appropriate changes in surface tension and the gas/liquid density ratio, jet behavior at ambient conditions in excess of the liquid critical point was observed to differ from behavior typical of jets injected at relatively low pressures. Furthermore, little

variation in wake intensity was seen, but this is conceivable considering the inherent difficulties in spontaneous Raman scattering, most notably, its intrinsic weakness.

II. List of Publications

Spegar, T. M. and D. A. Santavicca. An Experimental Study of Subcritical and Supercritical n-Pentane Jet Behavior in Nitrogen. JANNAF Propulsion Meeting, 1995.

Ondas, M. S. and D. A. Santavicca. The Development of an Exciplex Vapor/Liquid Visualization Technique to Study the Effect of an Acoustic Field on a Vaporizing Droplet. JANNAF Propulsion Meeting, 1995.

Ondas, M. S. and D. A. Santavicca. A Study of Droplet Vaporization in a Longitudinal Acoustic Field Using Exciplex Vapor/Liquid Visualization. ASME Symposium on Dispersed Flows in Combustion, Incineration and Propulsion Systems, Dallas, TX, 1997.

Prevish, T. D. and D. A. Santavicca. Droplet Breakup in Highly Turbulent Flows. 9th NASA Propulsion Engineering Research Center Symposium, Cleveland, OH, 1997.

Ondas, M. S., "The Development and Use of an Exciplex Vapor/Liquid Visualization technique to Study the Effect of Acoustic Field on a Vaporizing Droplet," Ph.D. Thesis, The Pennsylvania State University, 1997.

Prevish, T. D. and D. A. Santavicca. Turbulent Breakup of Hydrocarbon Droplets at Elevated Pressures. ILASS Americas, 11th Annual Conference on Liquid Atomization and Spray Systems, Sacramento, CA, 1998.

Prevish, T. D. Secondary Droplet Breakup in Highly Turbulent Flowfields. Ph.D. Thesis, The Pennsylvania State University, 1998.

III. List of Participating Scientific Personnel

Michael S. Ondas, Ph.D., 1997
Thomas D. Prevish, Ph.D., 1998
Timothy D. Spegar, Ph.D., 1999
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